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RESEARCH MEMORANDUM

FLOW DIFFUSION IN A CONSTANT-DIAMETER DUCT DOWNSTREAM

OF AN ABRUPTLY TERMINATED CENTER BODY

By Charles C. Wood and James T. Higginbotham

Langley Aeronautical Laboratory
Langley Field, Va.

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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FLOW DIFFUSION IN A CONSTANT-DIAMETER DUCT DOWNSTREAM OF AN ABRUPTLY TERMINATED CENTER BODY

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SUMMARY

A preliminary investigation of the flow properties of a constant-outer-wall annular diffuser in combination with a tailpipe has been conducted for the purpose of obtaining qualitative information which might lead to a short efficient configuration applicable to turbojet afterburners. The diffuser has an outer diameter of 21 inches, an area ratio of 1.9:1, and a 180° over-all equivalent conical angle of expansion. Tests were conducted with fully developed pipe flow at the diffuser-inlet station for inlet Mach numbers from 0.15 to 0.33 with corresponding Reynolds numbers from 0.53×10^6 to 1.06×10^6 when based on the inlet hydraulic diameter. The effects on the flow development of rectangular, noncambered vortex generators installed on the center body were determined for axial inlet flow and for an inlet flow having a 20.6° mean whirl angle.

With axial flow at the diffuser inlet, a vena contracta region formed immediately downstream from the center body terminal and rendered the first 1/2 diameter of tailpipe length ineffective. The introduction of a 20.6° whirl in the inlet flow apparently suppressed the vena contracta and resulted, when compared with axial inlet flow, in a 170-percent increase in the static-pressure rise and a 28-percent decrease in the total-pressure loss to the tailpipe station. The installation of vortex generators on the center body in the axial-flow case had little effect on the vena contracta formation but resulted in some improvement in pressure rise downstream from the vena contracta. For 20.6° inlet whirl angle, vortex generators eliminated the favorable effect of whirl and resulted in an over-all depreciation in the performance.

INTRODUCTION

The Internal Flow Section of the Compressibility Research Division at the Langley Laboratory is engaged in an extensive subsonic diffuser

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research program in which the performance characteristics of annular-diffuser designs applicable to turbojet afterburners are being studied. The program was initiated in an effort to develop configurations which provide stable flow, uniform diffuser exit-velocity distributions, and efficient performance. These goals were fixed by the desire to obtain better over-all performance from the power plant by eliminating combustion instabilities originating in the diffuser flow, by producing velocity distributions at the afterburner favorable to efficient combustion, by reducing diffuser losses especially in off-design operation, and by reducing excessive length and weight between turbine discharge and afterburner inlet.

Some data on the performance of annular diffusers are available in the literature in references 1 to 3. References 4 and 5 are the first two reports on investigations conducted in the subject program and consist of determinations of effective vortex-generator control arrangements for a 15° equivalent cone-angle diffuser with axial inlet flow (ref. 4) and with various degrees of inlet whirl angle up to 21° (ref. 5). Considerable improvements in the 15° diffuser performance were obtained through the use of vortex generators for flow control; however, it was desired to obtain comparable performance in a diffuser of shorter over-all length.

As a preliminary investigation designed to provide qualitative information leading to a short, efficient configuration (the extreme case), a combination abrupt expansion diffuser and tailpipe has been tested and the results are reported herein. Gibson (refs. 6 and 7) tested conical and rectangular single-wall diffusers with abrupt expansions and presented data in the form of maximum pressure rise to some point downstream. The goals of the subject program require, however, data on radial distribution of velocity in the tailpipe and the relation of static-pressure rise to tailpipe length. The effectiveness of vortex generators in accelerating the diffusion process and the effect of a whirling inlet flow are also required.

The investigation was conducted with fully developed pipe flow at the diffuser inlet at mean inlet Mach number varying from 0.15 to 0.33 with a resulting maximum Reynolds number of approximately 1.06×10^6 when based on the inlet hydraulic diameter. Tests were made with axial flow and with a mean inlet whirl angle of 20.6°. The 20.6° whirl angle is typical of a maximum value for most turbojet afterburner installations and is believed adequate to obtain the general effects of the whirling inlet flow on the diffuser performance. Tests were run with no flow controls and with vortex-generator arrangements used successfully for the diffuser of references 4 and 5.

SYMBOLS

p	static pressure
H	total pressure
χ	whirl angle, deg; measured with respect to diffuser center line
ρ	density
μ	coefficient of viscosity
u	local velocity
U	maximum velocity across an annular section
y	perpendicular distance from either diffuser inner or outer wall, in.
r	radius of duct, in.
M	Mach number
$\bar{p}$	weighted static pressure, $\dfrac{\int_{r_1}^{r_2} \rho upr\,dr}{\int_{r_1}^{r_2} \rho ur\,dr}$
$\bar{H}$	weighted total pressure, $\dfrac{\int_{r_1}^{r_2} \rho uHr\,dr}{\int_{r_1}^{r_2} \rho ur\,dr}$
$\bar{q}_c$	impact pressure, $\bar{H} - \bar{p}$

$\overline{X}$ weighted whirl angle, $\dfrac{\int_{r_1}^{r_2} \rho u X r \, dr}{\int_{r_1}^{r_2} \rho u r \, dr}$, deg

D hydraulic diameter, 0.541 ft or $\dfrac{4(\text{Cross-sectional area of duct})}{\text{Perimeter of duct}}$

R Reynolds number, $\rho_i V_i D_i/\mu_i$

$\overline{\Delta p}/\overline{q}_{ci}$ static-pressure coefficient, $\dfrac{\overline{p}_e - \overline{p}_i}{\overline{q}_{ci}}$

$\overline{\Delta H}/\overline{q}_{ci}$ diffuser-loss coefficient, $\dfrac{\overline{H}_i - \overline{H}_e}{\overline{q}_{ci}}$

δ boundary-layer thickness

δ^* boundary-layer displacement thickness, $\int_0^{\delta} \left(1 - \frac{u}{U}\right) dy$

θ boundary-layer momentum thickness, $\int_0^{\delta} \frac{u}{U}\left(1 - \frac{u}{U}\right) dy$

δ^*/θ boundary-layer shape parameter

Subscripts:

i diffuser inlet station

e tailpipe station

a axial component

1 reference to diffuser inner wall

2 reference to diffuser outer wall

APPARATUS AND PROCEDURE

Test Equipment

A diagram of the experimental setup is shown in figure 1. A more detailed diagram of the immediate area of the diffuser is shown in figure 2.

The setup consisted of an annular diffuser and tailpipe of constant outer diameter preceded by a section of annular ducting approximately 27 feet long. The diffuser had an outer diameter of 21 inches, an area ratio of 1.9:1, and a 180° over-all equivalent conical angle of expansion. The upstream annular ducting had a constant inner diameter of $14\frac{1}{2}$ inches and an outer diameter of 21 and 25 inches. All internal surfaces for several feet upstream of the diffuser inlet were filled and polished. Air entered the test apparatus through a 48-inch-diameter, 48-inch-long cylindrical chamber which was covered with cloth mesh. From this chamber air flowed through a 48-inch-diameter inlet bell, through the stators which established counterclockwise whirling action, as seen facing upstream, and through 27 feet of annular ducting to the diffuser inlet. The quantity of air passing through the experimental setup was controlled by an exhauster connected downstream of the diffuser exit.

Instrumentation

Stream total pressures, static pressures, and whirl angles were measured by remote-controlled survey instruments at both the diffuser inlet and tailpipe stations, 4 inches upstream and $22\frac{1}{2}$ inches downstream, respectively, of the end of the center body. (See fig. 2.) These stations are identical with those of references 4 and 5, and, therefore, permit a direct comparison of the performance of the two diffusers. A sketch of one of the survey instruments used in obtaining these measurements is shown in figure 3. Flow surveys were made at only one station at a time so that there were no instruments in the stream ahead of the measuring station. These surveys were made at four positions on the circumference of the duct, at each of the survey stations.

Static orifices extending from upstream of the diffuser inlet station to a point 21 inches downstream of the tailpipe station were installed along a single generatrix on the outer wall of the diffuser in order that an indication of the change in the flow pattern with diffuser length could be obtained.

Small tufts were used to observe the flow in the diffuser. These tufts were fastened along four generatrices approximately 90° apart on the outer wall of the diffuser. The tufts could be viewed through transparent windows in the outer wall of the diffuser.

Vortex Generators

NACA 0012 airfoils were used both for controlling separation and for straightening the flow. Regardless of the manner in which the airfoil was intended to function, it is referred to as a vortex generator. The angle setting of a vortex generator refers to the angle the center line of the vortex generator makes with the axis of the duct. When the angle between the diffuser center line and the vortex-generator center line lays in the same quadrant as the angle between the diffuser center line and the direction of flow, the angle setting is referred to as positive; when the angles lay in different quadrants, the angle setting is referred to as negative. Vortex-generator arrangements which had adjacent generators at the same angle setting are referred to as corotating arrangements; those arrangements which had adjacent generators at opposite angles are referred to as counterrotating arrangements. The longitudinal position of the vortex generators is referred to a plane passing through the 30-percent-chord station.

Two vortex-generator arrangements were tested; one arrangement for an inlet flow whirling at 20.6° and the other for axial flow. The two vortex-generator arrangements had been used previously in tests of the 15° diffuser of reference 5 and were responsible for appreciable improvement in diffuser performance. The arrangement used for axial flow consisted of twenty-four 3-inch chord, 1/2-inch-span generators set counterrotating at an angle setting of ±15°, whereas the arrangement for a whirling inlet flow consisted of twenty-four 3-inch-chord, $1\frac{9}{16}$-inch-span generators set corotating at -4°. Where configurations of reference 5 are mentioned, these two arrangements are those to which reference is made. The generators were located on the inner wall 5 inches upstream of the inner-body terminal; this position was several inches upstream of the location used in tests of the 15° diffuser of references 4 and 5. This change in location was necessary to prevent the vortex generators from overhanging the inner wall and, consequently, resulting in a serious reduction in their effectiveness.

Basis of Comparison

The description of the flow development and the effectiveness of each vortex-generator arrangement in promoting diffusion is presented in terms of the longitudinal distributions of static-pressure coefficient $\frac{p - \bar{p}_i}{\bar{q}_{ci}}$, the radial distributions of total-pressure coefficient $\frac{\bar{H}_i - H_e}{\bar{q}_{ci}}$, the static-pressure coefficient $\frac{p_e - \bar{p}_i}{\bar{q}_{ci}}$, the whirl angle X, and the velocity ratio u/U. The mean static-pressure coefficient $\overline{\Delta p}/\bar{q}_{ci}$, the mean diffuser-loss coefficient $\overline{\Delta H}/\bar{q}_{ci}$, and the mean flow angle $\bar{X}$ at the tailpipe station are also presented.

RESULTS AND DISCUSSION

Before the flow development in a diffuser can be studied, the nature of the flow entering the diffuser must be known. Data from the four survey instruments spaced about the circumference at the inlet station are presented in terms of the average total-pressure coefficient, the static-pressure coefficient, and the whirl angle in figure 4. Data are presented for an inlet pressure ratio $\bar{p}_i/\bar{H}_{ia}$ of approximately 0.95 for both axial flow and for a whirling inlet flow. Practically no variation in the distribution of the various parameters was observed with variation of inlet-pressure ratio. The inlet velocity profiles and associated boundary-layer properties at each of the four circumferential positions for the diffuser having axial inlet flow are presented in figure 5.

Axial Inlet Flow

Small tufts on the outer wall of the diffuser remained steady and axial for all tests.

Longitudinal static-pressure distributions.- In figure 6 are plots of the longitudinal distribution of static-pressure coefficient along the outer wall for the diffuser with and without vortex generators. Certain limited observations and conclusions can be made from these plots, although the radial distributions (see next section) indicate these pressure rises to be higher than the mean pressure rise. These curves indicate gradual decreases in static pressures, beginning at the inlet station and continuing downstream for approximately 16 inches, to values well below those present at the inlet station. No diffusion (pressures above those present at the inlet station) was realized for approximately the first 1/2 diameter of length downstream of the inner-body terminal. The effect of the vortex generators was to establish lower static pressures within the first 16 inches downstream of the inlet station and to accelerate the rate of diffusion commencing approximately 3 inches upstream of that noted without vortex generators. After about $1\frac{3}{4}$ tailpipe diameters downstream of the inner-body terminal, the vortex generators result in little improvement in static pressure. The curves realized with and without generators both appear to be approaching the theoretical or Borda-Carnot value of static-pressure coefficient (0.50), which (see ref. 6) should be realized within 5 tailpipe diameters from the inner-body terminal.

The initial decrease in static pressure is indicative of an effective flow-area reduction or the formation of a vena contracta. The flow pattern considered responsible for the vena contracta effect is illustrated in figure 7. The vortex generators had little effect on the magnitude of the vena contracta, but did promote an earlier and more rapid rate of mixing, as evidenced by greater static pressures, downstream from the vena contracta. (See fig. 6.) Downstream from the vena contracta the rate of static-pressure rise per inch of ducting for this diffuser without generators compares favorably with that of the 15° diffuser without generators. If the vena contracta effect could be eliminated by altering the design of the center body terminal, reasonably high static-pressure coefficients in lengths equivalent to the 15° diffuser probably could be realized in the absence of the center body cone, with the advantage of an effective weight reduction.

Radial distributions.- Radial distributions of total pressure, static pressure, whirl angle, and velocity ratio at the tailpipe station for the diffuser with and without vortex generators are shown in figure 8. Also included are the distributions observed at the diffuser inlet.

The distributions indicate a typical, abrupt, diffuser total-pressure-loss pattern for the diffuser without flow control; that is, extremely high losses of total pressure in a large region, approximately one-half of the cross-sectional area, near the center of the diffuser. In this region a substantial decrease in static pressure below that present near the outer wall is also observed. A center core, representing approximately 6 percent of the area, has no measurable velocity. The flow at the tailpipe station had a small angle of whirl which did not change appreciably across the duct.

The effects of the vortex generators on the distributions were to decrease substantially the magnitude of total-pressure losses in the region near the duct center, to establish small increases in total-pressure losses in a region near the outer wall, to decrease the static-pressure variation, and to increase the static pressure across the exit. These changes in total- and static-pressure distributions, by the use of vortex generators, are sufficient to establish some improvement in velocity profiles in the region near the center of the duct. This improvement in velocity distribution was accomplished with practically no change in u/U near the outer wall. The maximum velocity was reduced approximately 13 percent; this reduction indicates that vortex generators produce a more uniform velocity distribution by moving the air radially inward toward the center of the duct.

A comparison of the velocity distribution in the same measuring plane for the diffuser with vortex generators and for the diffuser having a 15° equivalent conical-expansion angle and no vortex generators (ref. 5) is given in figure 9 for each circumferential survey position. Although the curves for the four positions are not exactly symmetrical, they indicate the abrupt-diffuser—tailpipe combination to have a more favorable distribution near the outer wall and less favorable distribution near the center portion of the diffuser. The velocity distributions of the two diffusers, however, are equally poor.

Diffuser performance.- The static-pressure coefficient, diffuser-loss coefficient, and whirl angle at the tailpipe station are presented in figure 10 as a function of the inlet-pressure ratio for the diffuser with and without vortex generators. Increasing inlet-pressure ratio has a slightly adverse effect on the diffuser performance. The reason for the slightly negative angles of whirl is not known.

Calculated values of static-pressure and diffuser-loss coefficients as obtained by the Borda-Carnot relation (see ref. 6) can be compared directly with the no-control data, and have been noted in figure 10 at a value of $\bar{p}_i/\bar{H}_{ia}$ of 1.00 since the relation is for incompressible flow. It has been determined experimentally that tailpipe lengths equivalent to about 5 tailpipe diameters are required to realize these theoretical coefficients. The measurements in this investigation were taken at a tailpipe length of about 1 diameter. It appears probable, since the total-pressure loss realized at the 1-diameter station is somewhat greater than that predicted, that the total-pressure loss between the 1- and 5-diameter stations will be of sufficient magnitude to establish over-all losses substantially greater than predicted, and that the static-pressure rise between the 1- and 5-diameter stations will be of sufficient magnitude to establish static pressures at the 5-diameter station equal to those predicted. This condition is substantiated by the longitudinal pressure variation given in figure 6 and the large radial variation of velocity presented in figure 8.

Vortex generators result in substantial increases in both the static-pressure and loss coefficients over the entire Mach number range of the test. Increases in the respective coefficients of 77 and 22 percent above those obtained without generators were realized. The action of the vortex generators was not strong enough, however, to accelerate the mixing process to the point where efficient diffusion was obtained.

Data for comparison of the performance of this diffuser with that of an equivalent 15° diffuser are also presented in figure 10. Measurements were taken at the same measuring stations, thereby permitting direct comparison of results. The abrupt diffuser without generators accomplishes only 23 percent of the static pressure realized for the 15° diffuser; the abrupt diffuser with vortex generators accomplishes 38 percent of that realized for the 15° diffuser. The loss coefficient of the abrupt diffuser, with or without vortex generators, is much greater than that for the 15° diffuser. It is obvious from the standpoint of performance or when a saving in weight is not highly essential that continuation of the inner body, at least to the extent of eliminating the vena contracta region, whether operating without generators or with the present means of control, is important.

Whirling Inlet Flow

Small tufts located on the outer wall of the diffuser revealed the flow on the outer wall to remain attached and the whirling motion to increase with increasing distance downstream from the inlet station; this condition was expected and noted also for the 15° diffuser of reference 5.

Longitudinal static-pressure distributions.- In figure 11 are plots of the longitudinal outer-wall static-pressure distributions for the diffuser with and without vortex generators. As for axial flow the outer-wall static-pressure rise is greater than the mean. (See the following sections.) Examination of the curves indicates that minor changes in static pressure occurred upstream of the inner-body terminal, and that actual diffusion near the outer wall began only a short distance downstream. It is impossible to determine whether an actual reduction in effective flow area downstream of the center body occurred because of the large radial pressure gradient across the duct. It appears probable that the whirling flow tended to eliminate the vena contracta region and, consequently, to reduce the turbulence losses associated with the flow over the sharp corner terminating the center body; thus, the whirling flow effectively reduced the length of pipe required for diffusion. The effect of the vortex generators was to establish greater pressure on the outer wall to a point 10 inches downstream of the inner-body terminal and a lower pressure in the remainder of the tailpipe.

Radial distributions.- Radial distributions of total pressure, static pressure, whirl angle, and velocity ratio at the tailpipe station for the diffuser with and without vortex generators are presented in figure 12. Also included are the distributions observed at the diffuser-inlet station.

Comparison of the no-control case with that of axial flow indicates that, in the region near the outer wall where most of the flow was concentrated, the whirling inlet flow produced less total-pressure loss and more static-pressure rise than axial flow. The velocity distribution is more nearly uniform than for axial flow. These results are believed to be due to the same effect described in the preceding section; that is, the whirling flow near the inner wall in the region of the center body terminal effectively regulates the flow downstream of the terminal and, thus, reduces the length of the vena contracta region and the turbulence losses.

The effect of the vortex generators, set at an angle of attack of -4°, was to eliminate the favorable effect of whirl along the inner wall by reducing the whirl near the center body and thus create higher total-pressure loss and lower static-pressure rise at the tailpipe station. The generators reduced the radial static-pressure variation and reversed the direction of whirl near the center of the diffuser. The changes in total and static pressure and in whirl angle combined to produce a less favorable velocity distribution than for no control.

Comparison of the velocity distribution in the same measuring plane for the diffuser with vortex generators and for the 15° diffuser of reference 5 having the same vortex-generator arrangement (see fig. 13) indicates that the profiles for the abrupt diffuser are more favorable than for the 15° diffuser along the outer wall and in a small core near the center of the duct. However, the profiles for both diffusers are poor.

Diffuser performance.- The static-pressure coefficient, diffuser-loss coefficient, and whirl angle at the tailpipe station are presented in figure 14 as a function of the inlet-pressure ratio for the diffuser with and without vortex generators. The influence of inlet Mach number on the coefficients is minor for the Mach number range investigated.

For no control a whirling inlet flow increased the static-pressure coefficient about 170 percent relative to axial flow (see figs. 10 and 14) and reduced the loss coefficient about 28 percent for reasons discussed in the previous section. Vortex generators result in decreases and increases in the pressure and loss coefficient, respectively, when compared with the coefficients realized without vortex generators.

CONCLUSIONS

A preliminary investigation of the flow properties of a straight outer-wall, annular diffuser, tailpipe combination and the influence of vortex generators on the flow properties has been conducted for the purpose of obtaining qualitative information which might lead to a short efficient configuration applicable to turbojet afterburners. The diffuser has an outer-wall diameter of 21 inches, an area ratio of 1.9:1, and a 180° over-all equivalent conical angle of expansion. The tests were conducted with a fully developed pipe flow both for an axial inlet flow and for a 20.6° whirling inlet flow. The following conclusions are presented:

1. For the axial-flow case, immediately downstream from the center body terminal the flow forms a vena contracta region which renders the first 1/2 diameter of tailpipe length ineffective.

2. A comparison of the measured coefficients with those calculated by the Borda-Carnot relation, a relation for axial flow which has been found experimentally to apply to sudden-expansion diffusers followed by tailpipe lengths equal to 5 tailpipe diameters, indicates in the axial-flow case that, within about 1 diameter of tailpipe length, the major portion of the total-pressure loss has developed but only about 30 percent of the possible static-pressure rise has been produced because of the distortion still remaining in the velocity profile.

3. The vortex-generator installation has little effect on the magnitude of the vena contracta region in the axial-flow case and, although the installation promotes more rapid diffusion downstream from the first 1/2 diameter of tailpipe length, the performance up to the 1-diameter station is relatively inefficient.

4. The inlet flow whirling at 20.6° improves the static-pressure coefficient approximately 170 percent and decreases the loss coefficient about 28 percent relative to the values for axial flow. This improvement is attributed to an apparent suppression of the vena contracta formation and a consequent reduction in the turbulence losses associated with the flow over the sharp corner terminating the center body.

5. The installation of vortex generators straightens the flow near the inner wall and, thus, eliminates the favorable effect of rotation in this region and results in an over-all depreciation in the performance.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 17, 1953.

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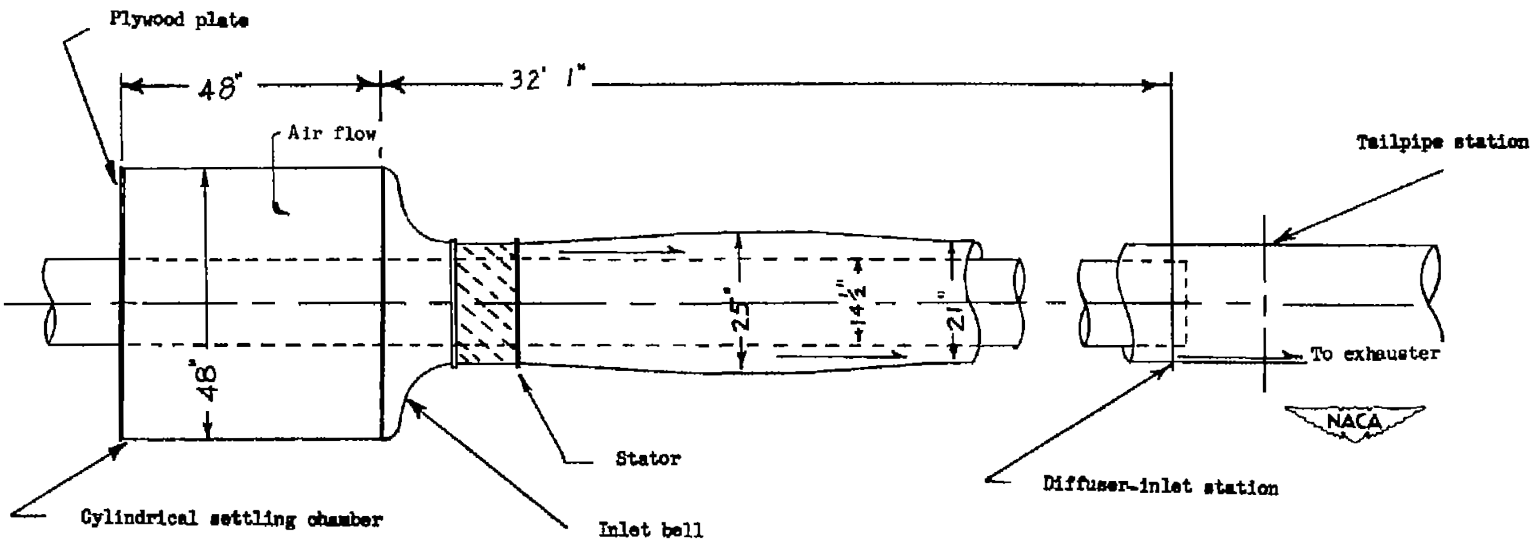

Figure 1.- Diagram of experimental setup.

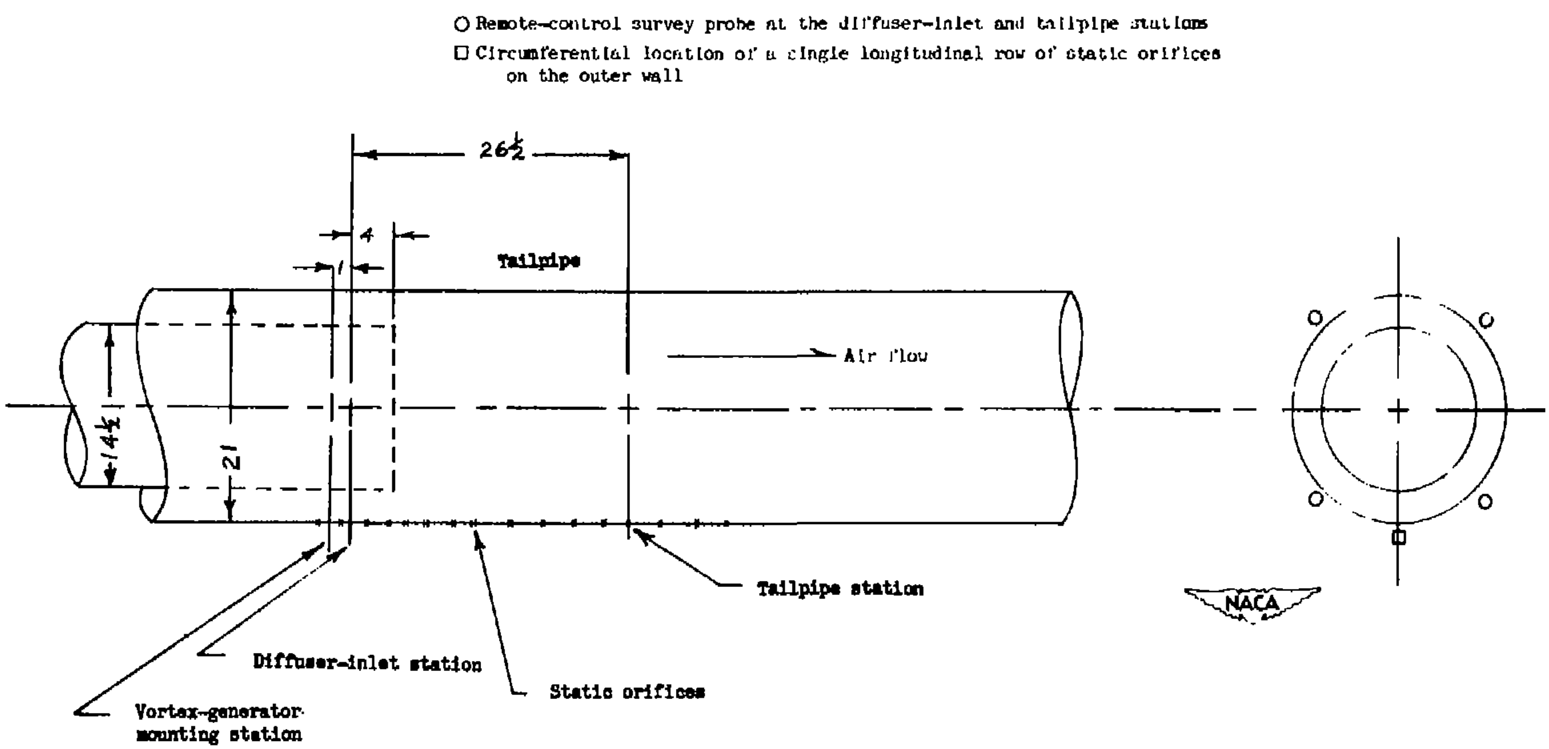

Figure 2.- Diagram of the diffuser tested. All dimensions are in inches.

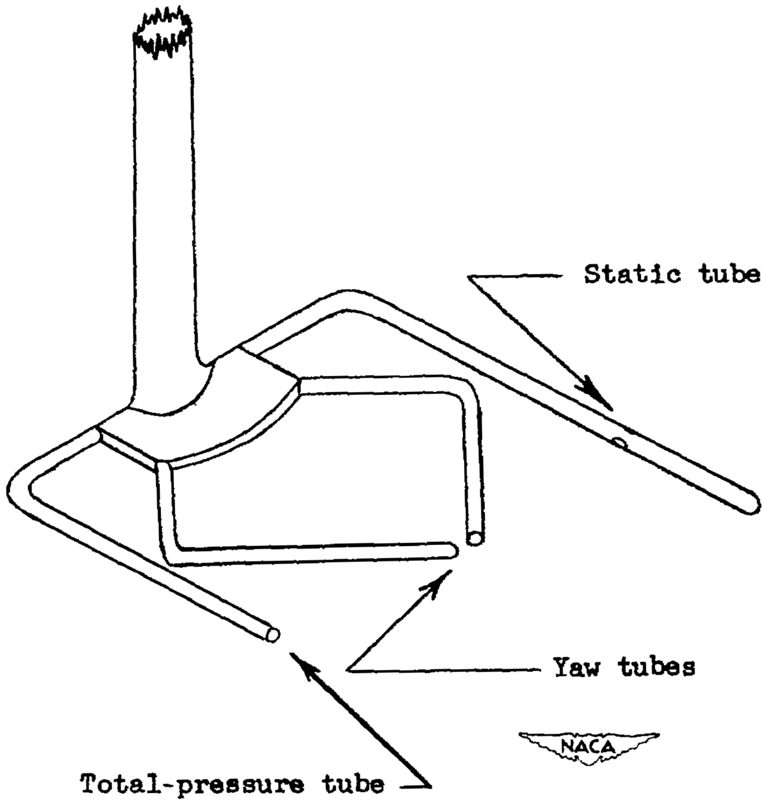

Figure 3.- Sketch of a typical survey instrument.

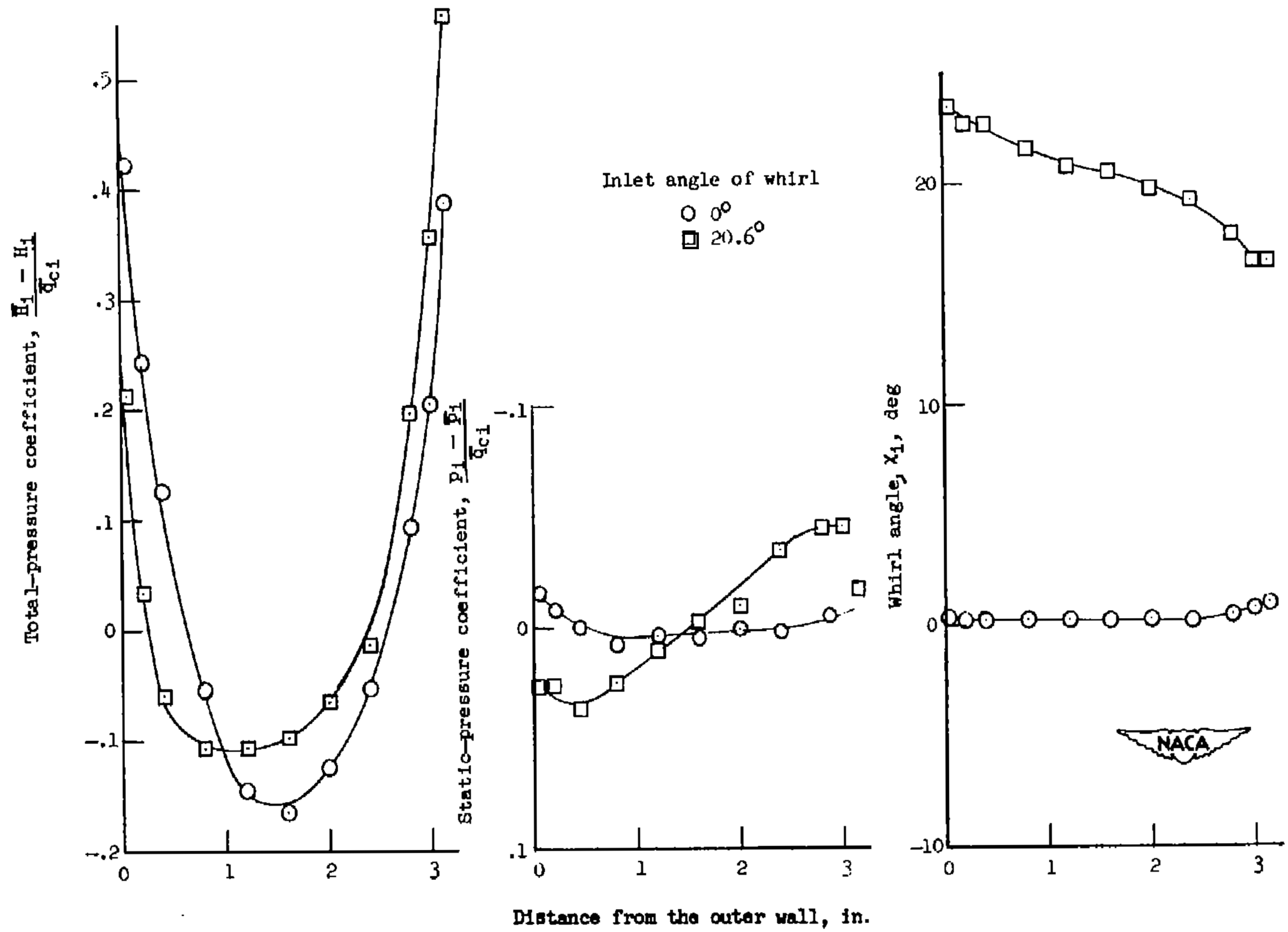

Figure 4.- Radial variations of total-pressure coefficient, static-pressure coefficient, and whirl angle at the diffuser inlet for two inlet-whirl angles. $\overline{p}_1/\overline{H}_{1a} \approx 0.95$.

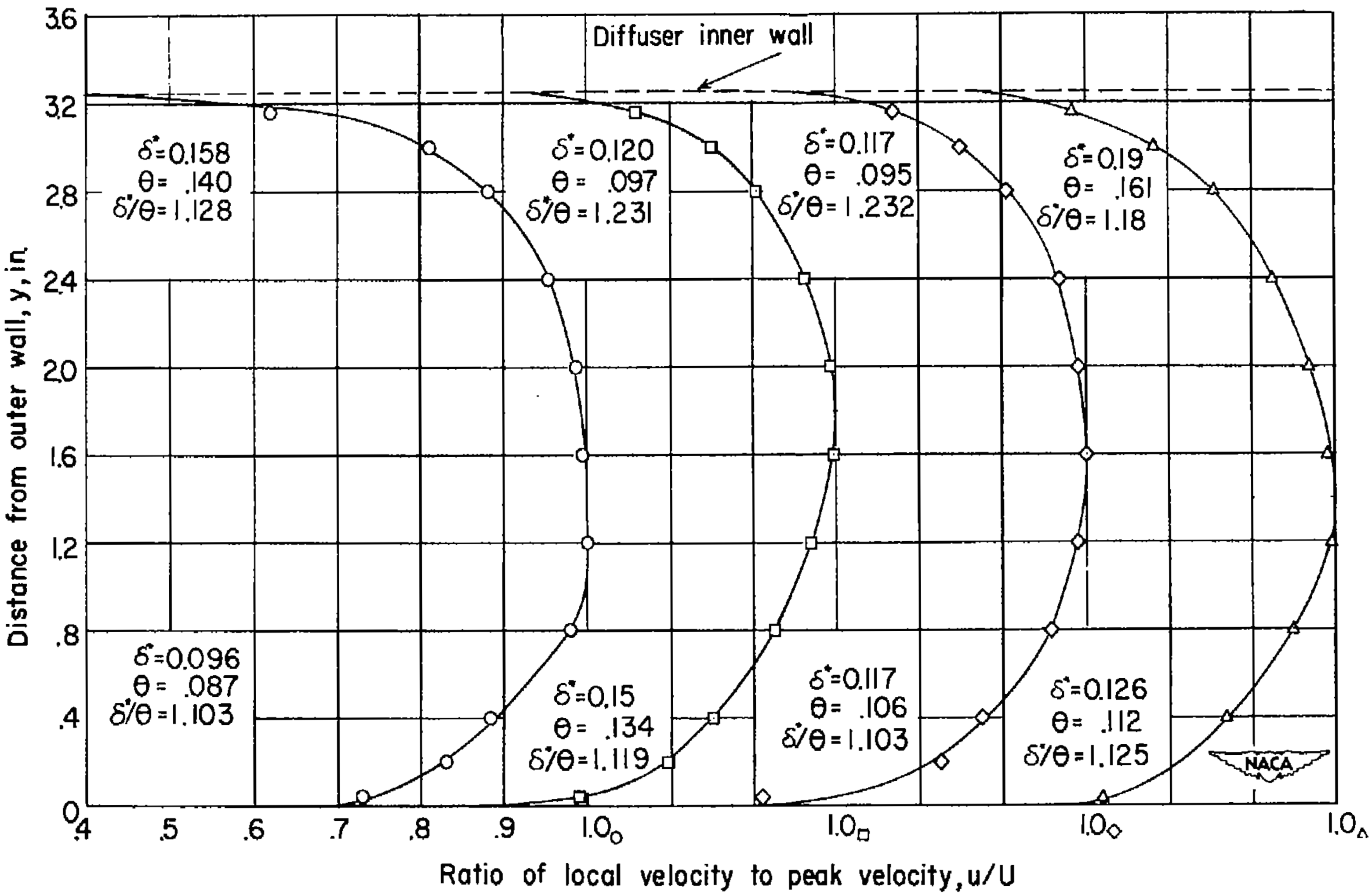

Figure 5.- Velocity profiles at four equally spaced sections around the diffuser-inlet station. $\bar{X}_i = 0^\circ$; $\bar{p}_i/\bar{H}_{ia} \approx 0.95$.

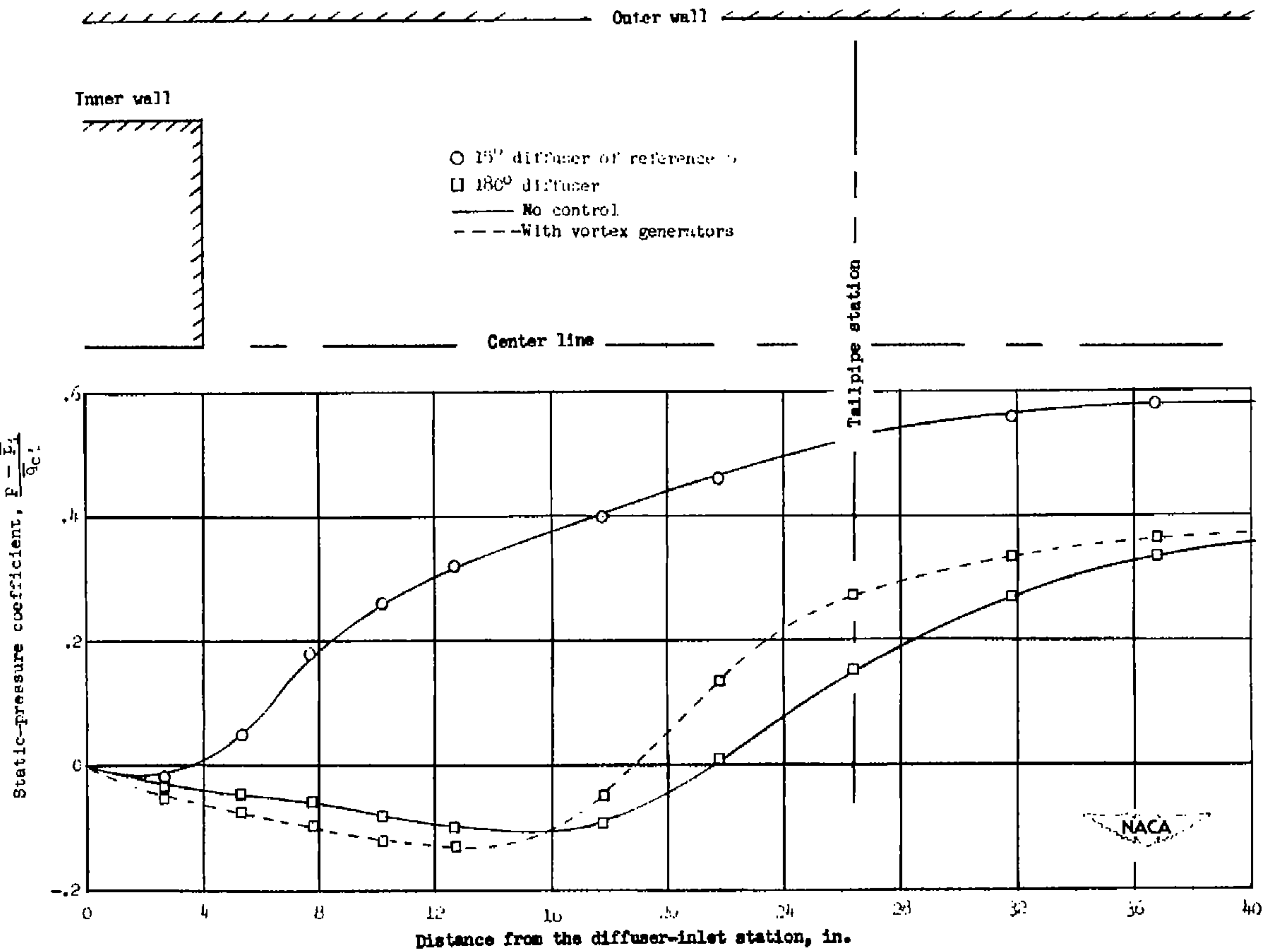

Figure 6.- Longitudinal distribution of static-pressure coefficient along the outer wall of the diffuser. $\overline{\chi}_i = 0^{\circ}$; $\overline{p}_i/\overline{H}_{1a} \approx 0.95$.

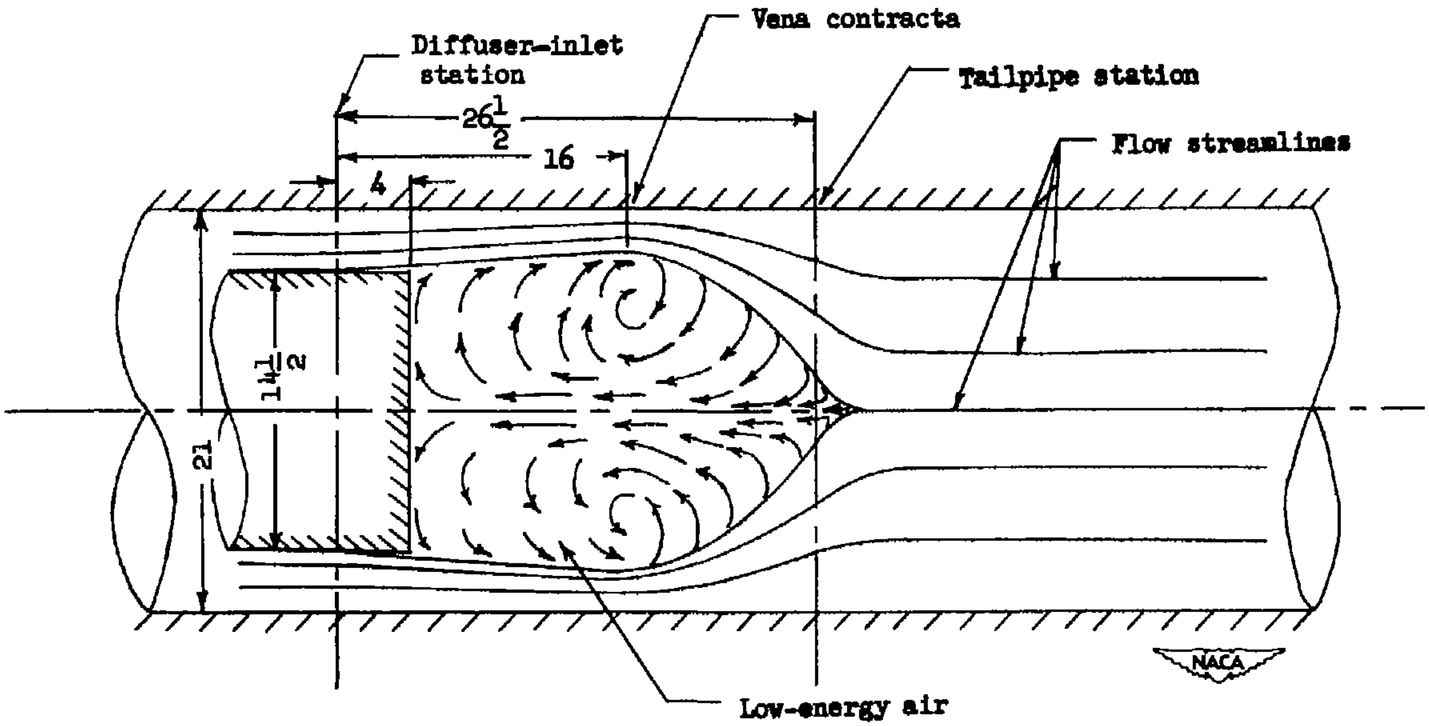

Figure 7.- Apparent flow pattern for the diffuser with axial flow. All dimensions are in inches.

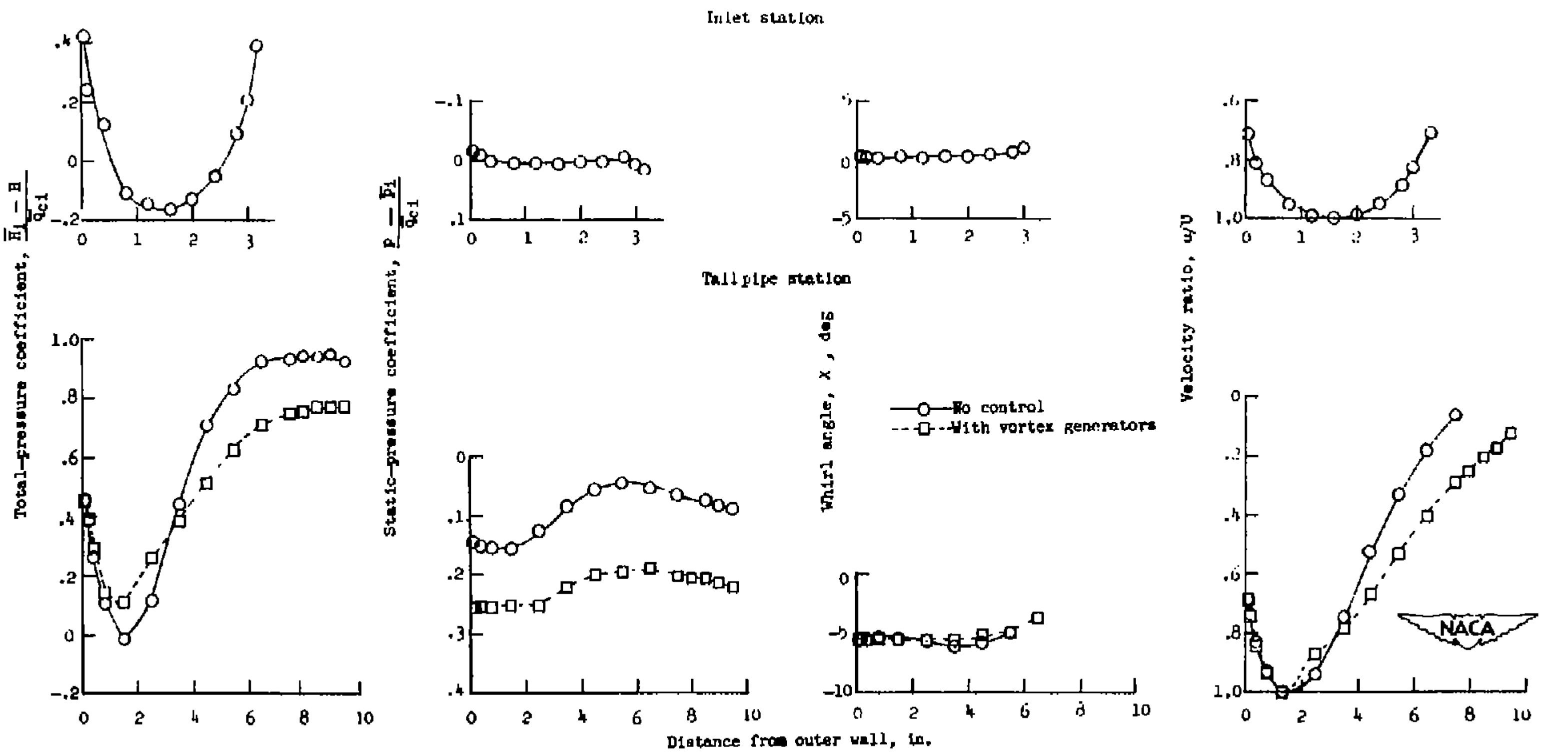

Figure 8.- Radial variation of total-pressure coefficient, static-pressure coefficient, whirl angle, and velocity ratio for the diffuser with no control and with vortex generators for control. $\bar{X}_i = 0^\circ$; $\bar{p}_i/\bar{H}_{1a} \approx 0.95$.

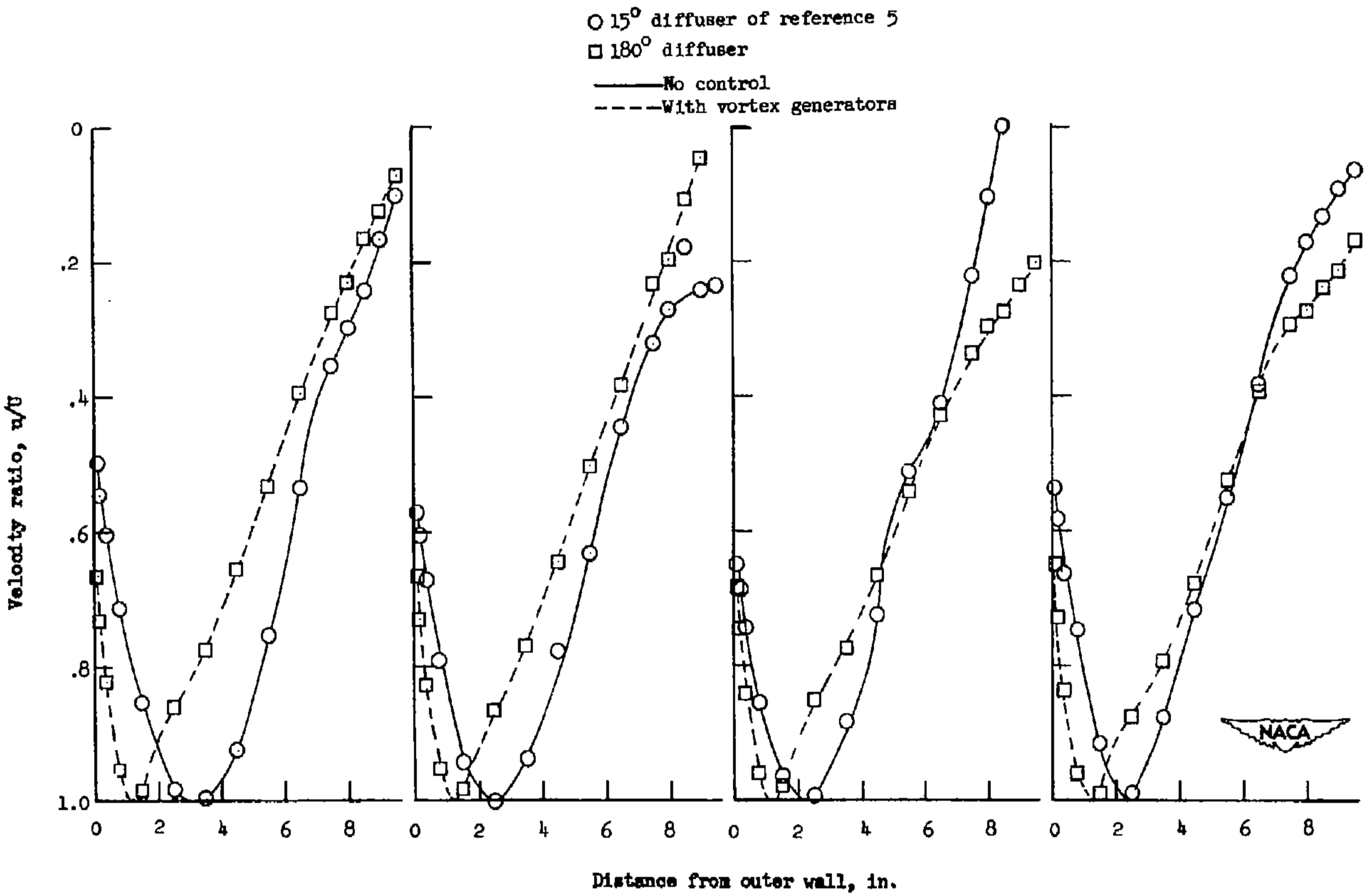

Figure 9.- Velocity profiles at the four circumferential survey positions at the tail pipe station. $\overline{X}_1 = 0^{\circ}$; $\overline{p}_1/\overline{H}_{1a} \approx 0.95$.

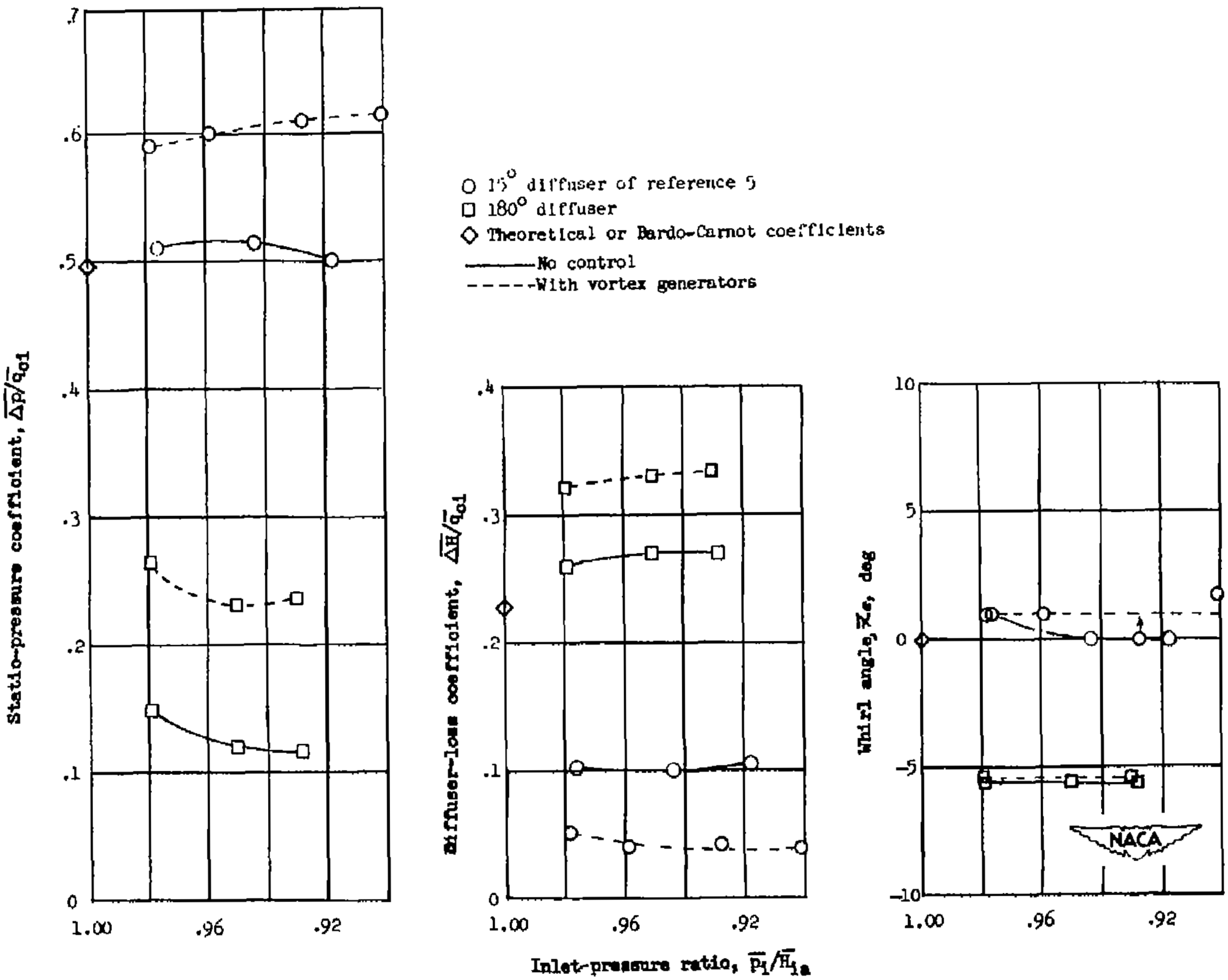

Figure 10.- Variation of static-pressure coefficient, diffuser-loss coefficient, and whirl angle with inlet pressure ratio. $\overline{\chi}_1 = 0^{\circ}$.

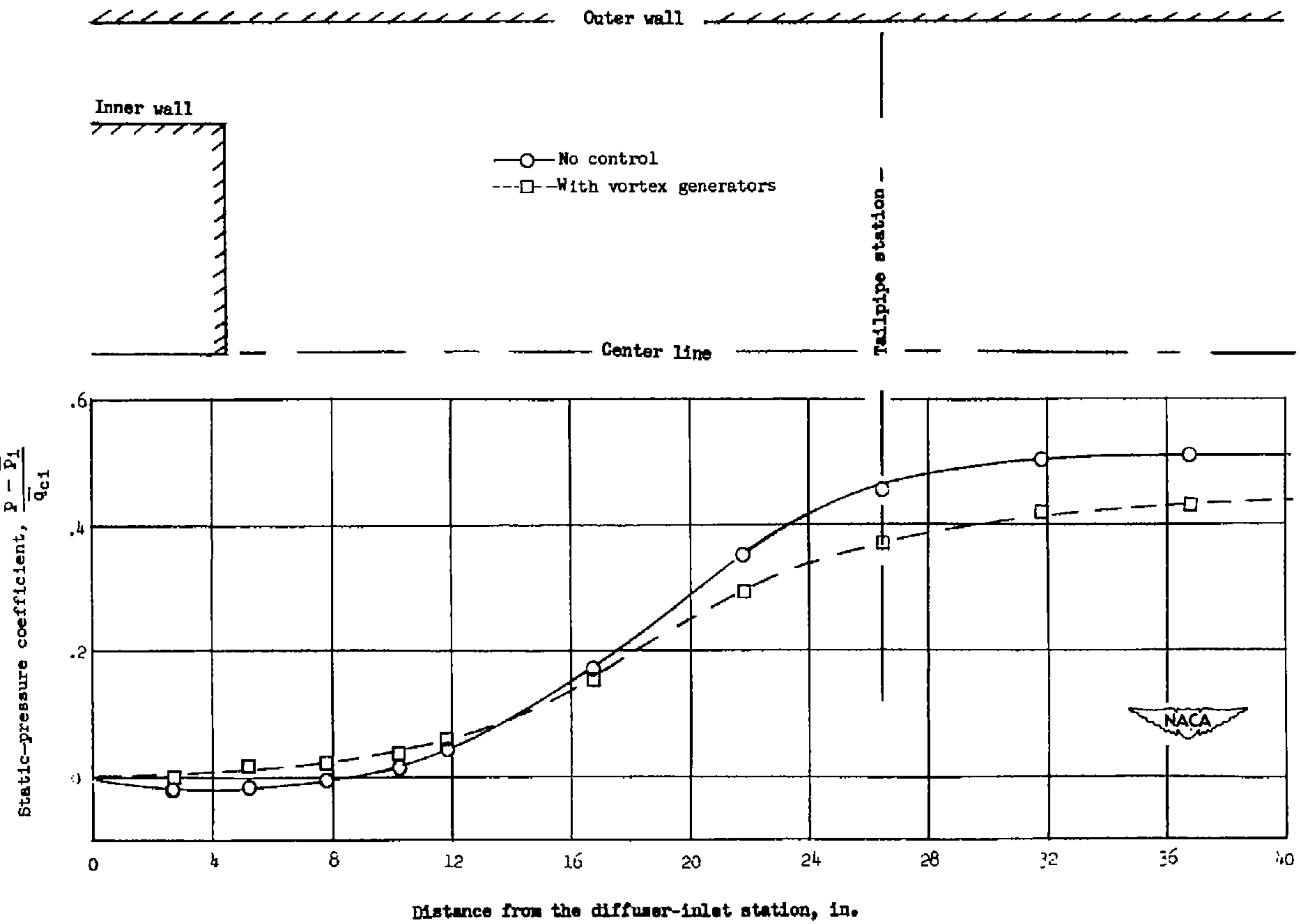

Figure 11.- Longitudinal distribution of static-pressure coefficient along the outer wall of the diffuser. $\bar{X}_i = 20.6^\circ$; $\bar{p}_i/\bar{H}_{ia} \approx 0.95$.

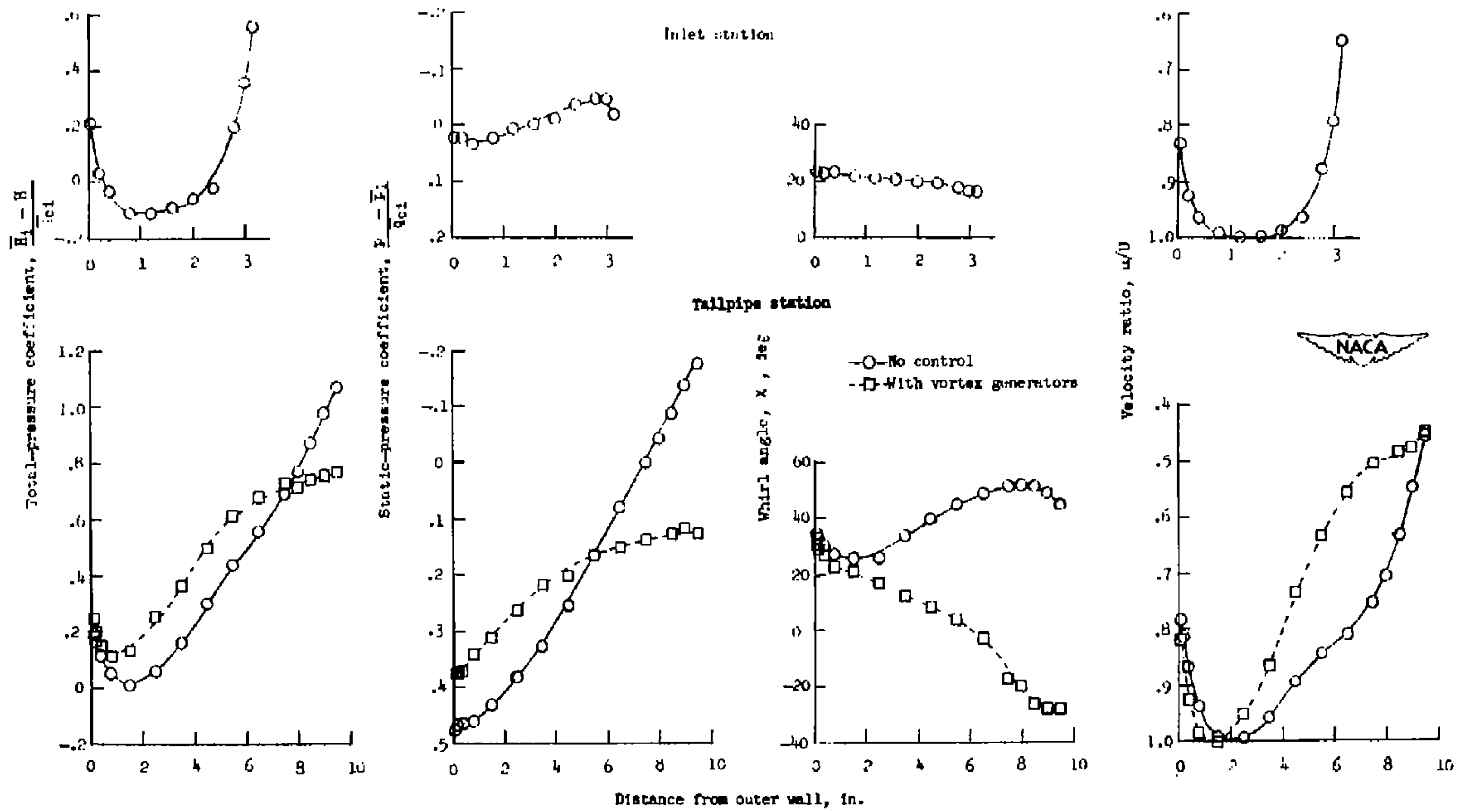

Figure 12.- Radial variation of total-pressure coefficient, static-pressure coefficient, whirl angle, and velocity ratio for the diffuser with no control and with vortex generators for control. $\overline{X}_1 = 20.6^{\circ}$; $\overline{p}_1/\overline{H}_{1a} \approx 0.95$.

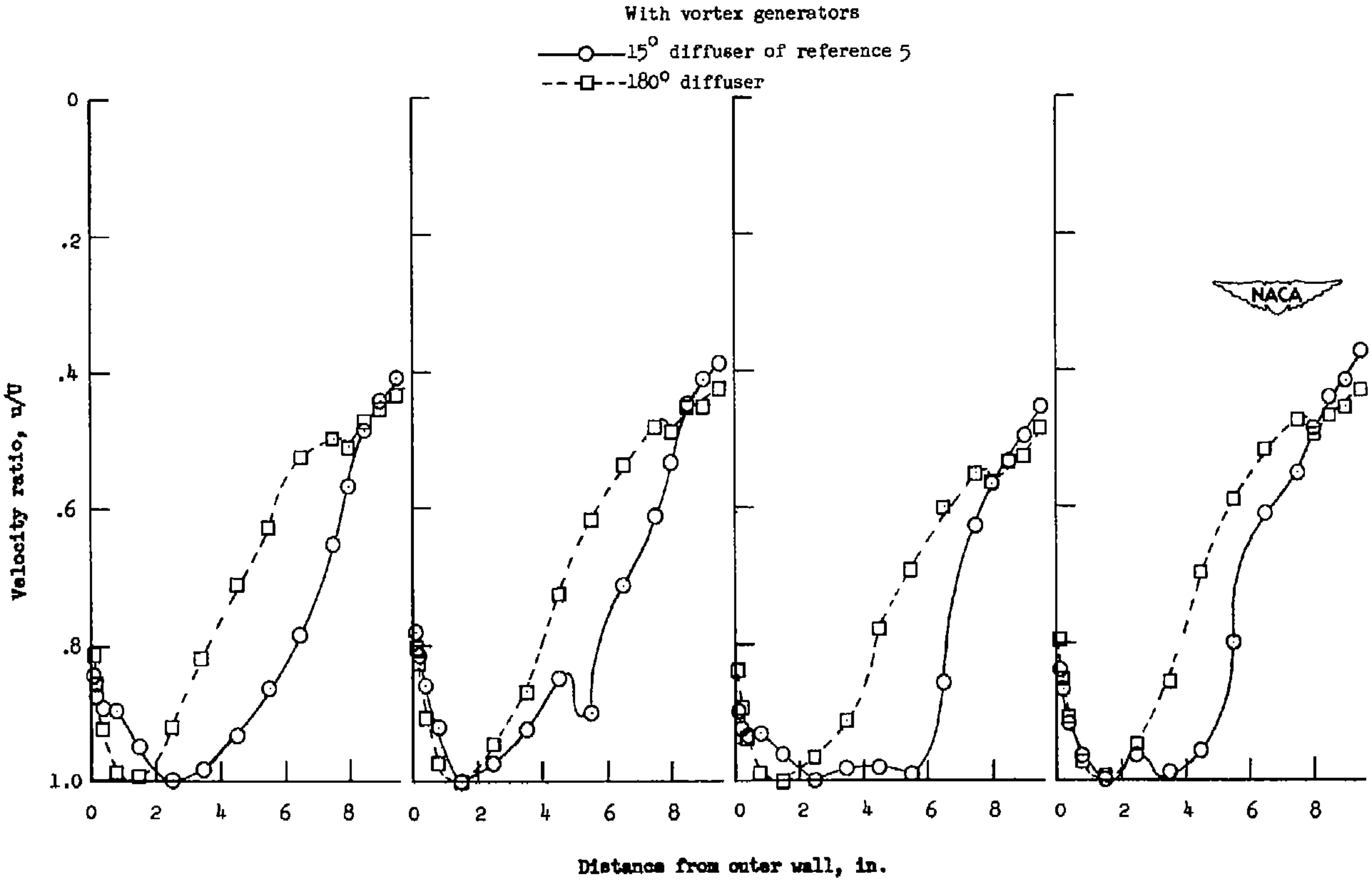

Figure 13.- Velocity profiles at the four circumferential positions at the tailpipe station. $\overline{X}_1 = 20.6^\circ$; $\overline{p}_1/\overline{H}_{1a} \approx 0.95$.

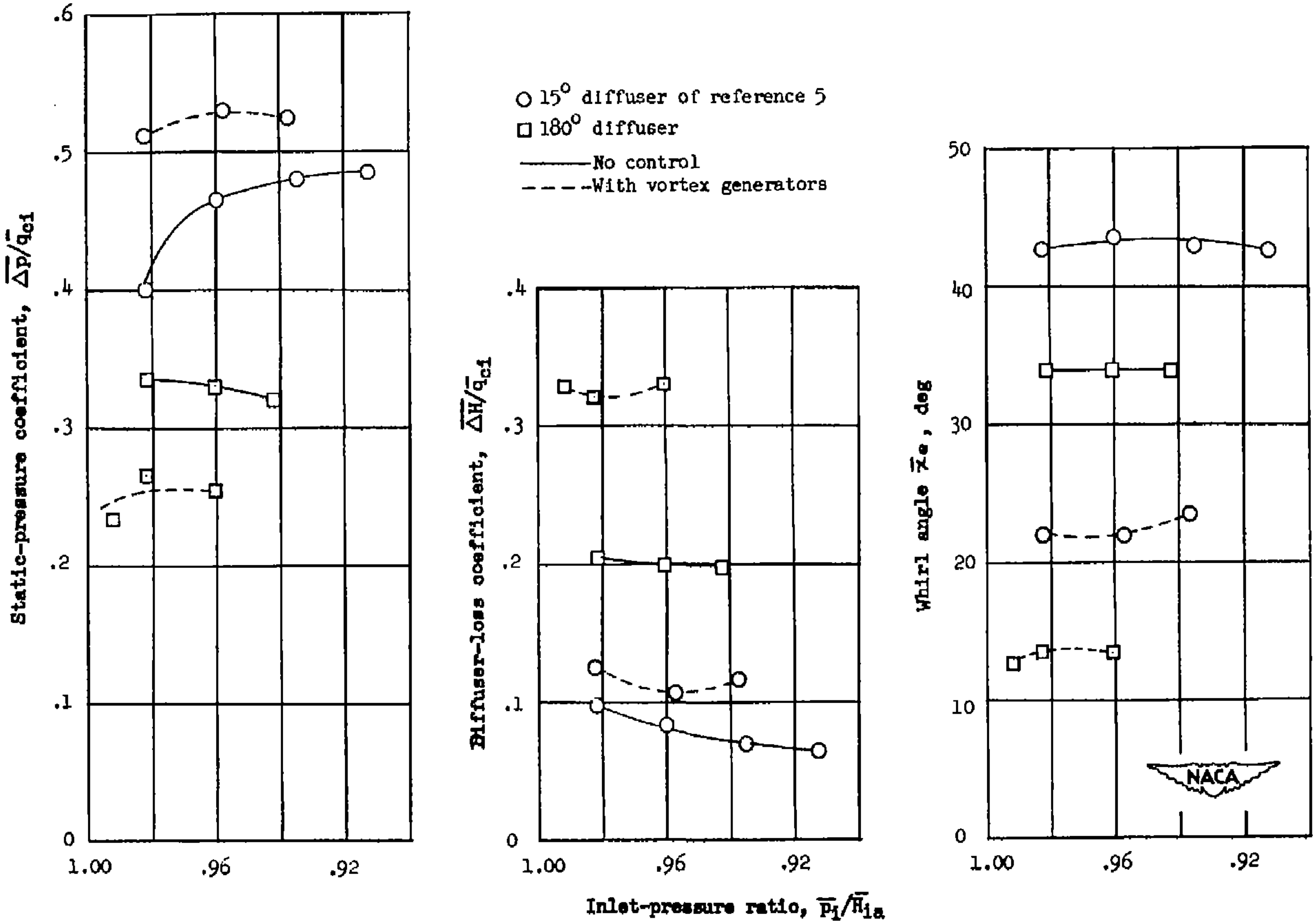

Figure 14.- Variation of static-pressure coefficient, loss coefficient, and whirl angle with inlet-pressure ratio. $\bar{\chi}_1 = 20.6^{\circ}$.

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